ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES ®

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IPC-TM-650 TEST METHODS MANUAL

Number	
2.5.5.7	
Subject	
Characteristic Impedance of Lines on Printed Boards by TDR	
Date	Revision
03/04	A
Originating Task Group	
TDR Test Method Task Group (D-24a)	

1 Scope This document describes time domain reflectometry (TDR) methods for measuring and calculating the characteristic impedance, Z_o, of a transmission line on a printed circuit board (PCB). In TDR, a signal, usually a step pulse, is injected onto a transmission line and the Z_o of the transmission line is determined from the amplitude of the pulse reflected at the TDR/transmission line interface. The incident step and the time delayed reflected step are superimposed at the point of measurement to produce a voltage versus time waveform. This waveform is the TDR waveform and contains information on the Z_o of the transmission line connected to the TDR unit.

Note: The signals used in the TDR system are actually rectangular pulses but, because the duration of the TDR waveform is much less than pulse duration, the TDR pulse appears to be a step.

1.1 Applicability The observed voltage or reflection coefficient change in the TDR waveform is related to the difference between Z_o of the transmission line and the impedance of the TDR. If the impedance of the TDR unit is known via proper calibration, then the Z_o of the transmission line attached to the TDR unit may be determined. Thus, the TDR method is useful for measuring Z_o and changes in Z_o of a transmission line. These impedance values thus determined can be used to verify transmission line design (engineering development), measure production repeatability, and qualify manufacturers via transfer or artifact standards.

Engineering development requires detailed information on the electrical performance of prototype units to assure the transmission line design yields the expected performance characteristics. Detailed laboratory analysis of the effect of variations in design features expected in actual manufacture can be done to assure the proposed design can be manufactured at a useful quality level.

1.2 Measurement System Limitations Measurements of Z_o often vary greatly, depending on equipment used and how the tests were performed. Following a specified method helps assure accurate and consistent results. Both single-ended and differential line measurements have limitations in common, including the following:

a. The Z_o measured units are derived and not directly measured.

b. The value of characteristic impedance obtained from TDR measurements is traceable to a national metrology institute, such as the National Institute of Standards and Technology (NIST), through coaxial air line standards. The characteristic impedance of these transmission line standards is calculated from their measured dimensional and material parameters.

c. A variety of methods for TDR measurements each have different accuracies and repeatabilities.

d. If the nominal impedance of the line(s) being measured is significantly different from the nominal impedance of the measurement system (typically 50 Ω), the accuracy and repeatability of the measured numerical valued will be degraded. The greater the difference between the nominal impedance of the line being measured and 50 Ω, the less reliable the numerical value of the measured impedance will be.

e. Measurement variation (repeatability, reproducibility) may only be a small component of the total uncertainty in the value of the characteristic impedance. For example, if the uncertainty in the characteristic impedance of the reference air line is ± 0.5 Ω (for a 95 % confidence interval), then the uncertainty in the measured characteristic impedance of the test line can be no better than ± 0.5 Ω even if measurement variation is much less.

f. The particular TDR methods described herein are not suited for measuring the characteristic impedance as a function of position along the transmission line (impedance profiling) because signal reflections within the transmission line under test and between the TDR unit and transmission line under test may adversely affect measurement results.

g. The requirements for the length of the transmission line under test given in Section 3 of this test method as well the IPC-2141 must be met.

Further measurement considerations and notes are provided in Section 6.

1.3 Sample Limitations The type of test sample used may also impact Z_o values (see IPC-2141). The sample-based limitations include:

a. The transmission line under test varies along its length whereas the value of Z_0 obtained assumes a uniform transmission line. Therefore, the measured Z_0 only approximates the characteristic impedance of an ideal line that is representative of the line under test.

b. Lines on a printed circuit board may deviate significantly from design. For example, microstrip lines longer than 15 cm [5.91 in] on boards with plated-through holes often have variations in line width; this variation is due to plating and/or etching variations.

c. If the transmission line is too short, the accuracy of the calculated impedance value may be degraded (see 4.1.2). If the transmission line is too long, skin effect and dielectric loss may cause a bias in the impedance measurement.

d. Depending on where the measurements are made, the value of Z_0 obtained may be affected by dielectric and conductor loss and other effects. The farther away from the interface between the probe and the transmission line under test, the worse these effects will be.

e. Duration of the measurement window (waveform epoch) may need to be adjusted for sample length and location of midpoint vias along the transmission line.

2 Reference/Applicable Documents

IPC-2141 Controlled Impedance Circuit Boards and High Speed Logic Design

IPC-TM-650 IPC Test Methods Manual

1.9 Measurement Precision Estimation for Variables Data

3 Test Specimens The test specimen can take one of several forms, depending on the application, but contains at least one transmission (or interconnect) test structure. As examples, four types are mentioned in 3.1.1 through 3.1.4. The transmission lines to be measured may be of either stripline or microstrip construction and configured as either single-ended or differential. See IPC-2141 for a recommended test coupon design.

3.1 Test Specimen Examples

3.1.1 Example 1 Representative samples of the actual PCB being manufactured are selected. In some cases, this sample set may contain all of the boards. Agreed upon functional or nonfunctional transmission lines within the sample are used for the measurement. Criteria for selection of such lines includes:

a. Inclusion of the PCB's critical features.

b. Accessibility of terminations for the line.

c. Absence of branching.

d. Absence of impedance changes within the transmission line under test.

e. Representation of controlled Z_0 signal layers in a multi-layer board.

3.1.2 Example 2 Representative samples should be as in 3.1.1, except that the test lines are nonfunctional lines designed into the board for easy termination for TDR measurements. Such test lines should be planned to include critical features typical of functional lines and should lie in controlled Z_0 signal layers.

3.1.3 Example 3 Representative samples should be as in 3.1.1, except test coupons are cut from the master board at the time the individual PCBs are separated. Such test coupons will have one or more sample transmission lines with termination suited for testing. Such test lines should include critical features typical of functional lines and will be fabricated in the same configuration and structure as the master board on the same controlled Z_0 layers.

3.1.4 Example 4 A sample of the substrate laminate to be characterized before use in manufacturing PCBs is fabricated with test transmission lines. The fabrication may involve laminating several board layers together in the same manner anticipated for PCB manufacture.

3.2 Identification of Test Specimen For specimens of types called out in 3.1.1, 3.1.2, or 3.1.3, a board serial number, part number, and date code should be adequate. Specimens from 3.1.4 should include whatever lot or panel identification is available for the substrate laminate being evaluated.

3.3 Conditioning If conditioning is required, test specimens shall be stored before testing at 23 °C (+1/-5) °C [73.4 °F (+ 1.8/-0 °F)] and 50 % RH ± 5 % RH for no less than 16 hours. If a different conditioning procedure is used, it must be specified by the user.

4 Equipment and Instrumentation The TDR measurement system contains a step generator, a high-speed sampling oscilloscope, and all the necessary accessories for connecting the TDR unit to the device under test. IPC-2141 provides a short discussion of the TDR system architecture, system considerations, and the TDR measurement process.

1.1 Measurement System Requirements

4.1.1 Measurement Accuracy The measurement accuracy of the TDR should be sufficient to provide the required accuracy in the value of characteristic impedance. The required measurement accuracy of the TDR unit will depend on the TDR measurement method. In general, the measurement accuracy of the TDR unit should be better than 1% of amplitude (either voltage or reflection coefficient). Noise in the measured values will affect the uncertainty in the calculated Z_o values. The value of Z_o may be affected by the length of the transmission line under test and the section of the transmission line from which Z_o is calculated (see 3.1.1.d).

4.1.2 Temporal/Spatial Resolution The resolution limit of a given TDR unit is defined as that particular time or distance wherein two discontinuities or changes on the transmission line being measured, that would normally be individually discernable, begin to merge together because of limited TDR system bandwidth. The resolution limit is specified in either time or distance, and is always related to the one-way propagation time between the two discontinuities, T_P (see Figure 4-1), and not the round trip propagation time.

Per this definition, the resolution limit is:

a. half the system risetime, t_{sys}, where t_{sys} is the 10 % to 90 % risetime or 90 % to 10 % falltime (depending on whether the TDR response is calibrated with a short or open circuit), or

b. 0.5 t_{sys} x v_p, where v_p is the signal propagation velocity in the transmission line being measured.

These definitions are complementary.

For a given length of transmission line to be measured, the resolution should not exceed one fourth (0.25) of the available length, L_{TL} of the transmission line. Table 4-I provides examples of required resolution for typical surface microstrips in air, and on FR4 circuit board ($v_p \approx 2x10^8$ m/s), for a given TDR system risetime.

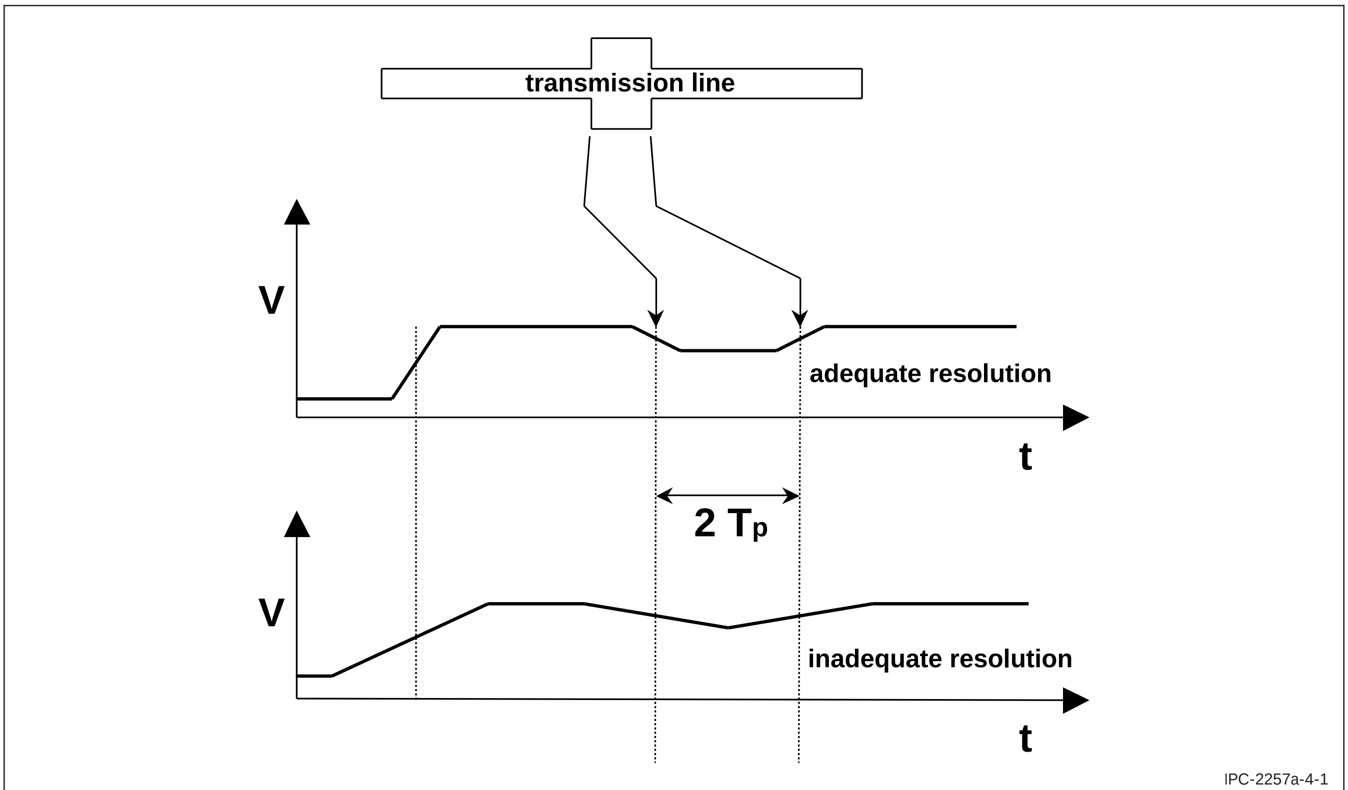

Figure 4-1 Resolution and Electrical Length of Transmission Line

Table 4-I Resolution of TDR Systems

TDR System Risetime	Resolution	4X Resolution
10 ps	5 ps / 1 mm [0.04 in]	4 mm [0.16 in]
20 ps	10 ps / 2 mm [0.08 in]	8 mm [0.31 in]
30 ps	15 ps / 3 mm [0.12 in]	12 mm [0.47 in]
100 ps	50 ps/ 10 mm [0.39 in]	40 mm [1.57 in]
200 ps	100 ps / 20 mm [0.79 in]	80 mm [3.15 in]
500 ps	250 ps / 50 mm [1.97in]	200 mm [7.87 in]

Intermediate values can be linearly interpolated from Table 4-I or using:

$$t_{sys} \le \frac{L_{TL}}{2} \frac{1}{v_p}$$

For example, if a 32 mm [1.26 in] long transmission line was being measured, a TDR system with $t_{sys} \le 80$ ps should be used. Note that, if the probe launch caused excessive ringing in the TDR waveform, or if the launch does not repeatably replicate the connection to the standard, then the 0.25 factor may need to be smaller.

4.2 TDR Requirements

4.2.1 Impedance The impedance of the TDR unit should be 50 Ω with an impedance uncertainty less than or equal to ± 0.5 Ω. This TDR impedance value is selected because it is the impedance used by most high-speed/high-frequency test instrumentation and compatibility with this instrumentation is necessary for characterizing the dynamic TDR properties, such as its impulse response (or transfer function). The impedance of the TDR unit should be calibrated using an artifact standard, such as an air line (see 4.3.6). However, the TDR impedance is a function of frequency and calibration using a fixed region of the TDR waveform (the measurement zone) will only yield an average impedance value for the TDR unit for the corresponding frequency range.

4.2.2 Timebase Accuracy The horizontal timebase accuracy defines how well the TDR instrument's horizontal time scale can display the correct length of the trace. This affects both the accuracy of the measurement zone calculations and any propagation delay values. The timebase accuracy should be less than 0.25 t_{sys} (see also 4.1.2).

4.2.3 Step Aberrations The ability of the TDR instrument to measure the impedance of a transmission line is related to how well the instrument can generate a step-pulse with a minimum of aberrations (ringing, overshoot, undershoot, settling, etc.). Any ringing, overshoots, or undershoots will cause corresponding aberrations in the TDR waveform (see Figure 4-2). These aberrations can cause significant errors in the impedance value computed from the TDR waveform. Additionally, low frequency step aberrations may produce a ramp in measurement zone. This ramp can cause a significant bias in the computed impedance value. The TDR instruments step aberrations should be less than 1% of the total step amplitude. For example, the impedance error shown in Table 4-2 is for a 1 mV error of a 250 mV step. Poor settling and large

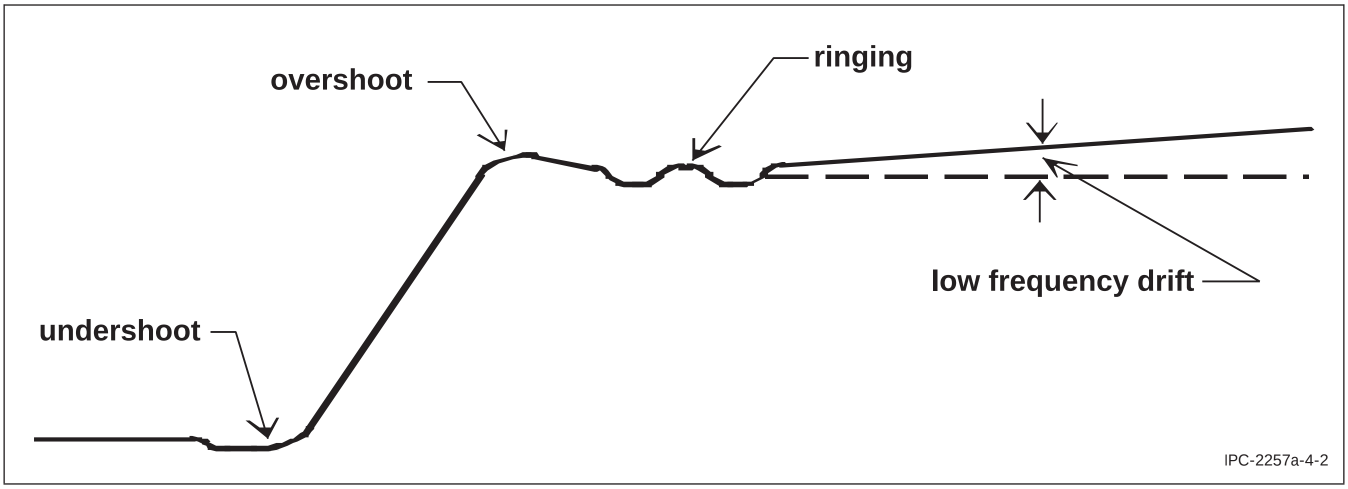

Figure 4-2 Potential TDR Step Aberrations

aberrations will increase the variation in the average voltage or reflection coefficient value from which Z_0 is computed, thereby increasing the variation in the compute value of Z_0.

Table 4-2 Impedance Error

Impedance Error	Transmission Line Impedance
0.24 Ω	28 Ω
0.4 Ω	50 Ω
0.79 Ω	90 Ω
1.23 Ω	125 Ω

4.3 Other Equipment Requirements

4.3.1 Connectors TDR systems typically come with either ''SMA,'' 3.5 mm, or 2.92 mm connectors at their measurement ports. SMA, 3.5 mm, and 2.92 mm connectors are all 50 Ω connectors and are electrically and geometrically compatible, therefore, they can be mated directly to each other. However, the 2.92 mm and 3.5 mm connectors are precision connectors (have a lower impedance uncertainty than the SMA) and are designed to provide a more repeatable connection than the SMA connector. Therefore, for accurate measurements, it is recommended that the 2.92 mm or 3.5 mm connector be used where possible. The bandwidth of the connectors must be great enough so that the connectors do not affect the accuracy of the TDR measurement. The typical -3 dB bandwidth of 3.5 mm connectors is approximately 34 GHz and of SMA connector is approximately 24 GHz. The reflection and insertion losses of the connector should be less than 27 dB and 0.3 dB respectively. Other connectors, comparable in performance to the 3.5 mm connector, may also be used. All cable connections using SMA, 3.5 mm, or 2.92 mm connectors should be tightened with a torque wrench to following specification, unless otherwise specified by the manufacturer of the connector or cable:

Table 4-3 Connector Torque Specifications
[Conversion factor is 0.1128 N-m/(lb-in)]

Connector Type	Required Torque
SMA	0.56 N-m [5 lb-in]
3.5 mm 2.92 mm, K	0.9 N-m [8 lb-in]

4.3.2 Cabling All test cables should be coaxial and have a characteristic impedance of 50 Ω with an impedance uncertainty of less than ± 1 Ω. Cables used in the measurement circuit of the transmission line under test should have connectors that are compatible with the rest of the measurement system. The bandwidth of the cable must be great enough so that the cable does not affect the accuracy of the TDR measurement. The length of the cables should be kept to a minimum. The total insertion loss (including connector loss) of the cabling connecting the transmission line under test to the TDR should be kept to a minimum, for example, less than 0.033 dB/cm [1db/foot] at 26.5 GHz. Table 4-4 contains suggested maximum cable lengths. Faulty cables can contribute up to a 1 Ω error. Cable connections should be tightened with a torque wrench to ensure a good connection.

Table 4-4 Maximum Suggested Cable Lengths

TDR Cable Assembly	TDR Cable Length
Sampling Unit to Static Isolation Unit	30 cm [12 in]
Static Isolation Unit to In-Line Secondary Standard	91 cm [36 in]
In-Line Standard (such as, semi-rigid coaxial cable)	10 cm [4 in]

4.3.3 Probes The probe assembly should have a characteristic impedance of 50 Ω or of approximately the same value as that of the transmission line under test, with an uncertainty of ±1.0 Ω or less. The probe tips should be of sufficient diameter and pitch (spacing between signal and ground tips) to accurately and repeatably probe the desired probe contact pad geometry. (See IPC-2141 for recommended probe landing layouts for TDR coupons.) Single-ended probes should contain two tips, one each for the signal and ground lines. Differential probes should contain two tips for contacting the signal lines and one or two tips for contacting the reference plane or planes. The probe tips should have moderately sharp edges to cut through any oxides. For hand held probe assemblies, the probe handle should be ergonomically shaped. The probe bandwidth should be sufficient for the desired temporal/spatial resolution (see 4.1.2). The probe settling time should be short so as not to affect the duration of the measurement zone. The overall performance of the probe can be incorporated into the TDR system response for computing TDR system temporal/spatial resolution (see 4.1.2). Inconsistent probe force and placement is common and can cause a significant yet unknown error that can exceed 5 Ω. Probe connections should be tightened with a torque wrench to ensure a good connection.

4.3.3.1 Probes for Differential Structures The differential probe should be long enough to act as a transfer standard, similar to that described in 4.3.7 for testing single-ended transmission lines (see 5.2.1). This probe can be constructed using a printed circuit board differential transmission line that has a differential impedance similar to the traces being tested or by using short identical lengths of semi-rigid cable that connect the instrument cables to the differential probe. The probe or semi-rigid cable should be sufficiently long to provide an adequate duration for the measurement zone (see 4.1.2) used during calibration and measurement.

4.3.4 Terminations Many instruments perform differently under different electrical loads. If a test is performed with open circuited lines, the calibration of the reference should also be done using an open circuit termination.

4.3.5 ESD Protection Static build up on specimens prior to test can damage the sampling heads in the TDR equipment. Therefore, it is recommended that ESD protection be used. Such protection can be supplied internally to the TDR system or externally. If supplied externally, using a coaxial switch for example, then the switch should be placed between the transmission line under test and the TDR instrumentation. The switch, or static protection device (SPD), should have a return and insertion loss less than 16 dB and 0.3 dB at 18 GHz. A maximum of 31 cm [12.2 in] of high quality, high frequency cable may be used to connect the TDR instrument to the protection switch. Samples should be grounded to remove any residual static and/or passed through some type of deionization device prior to testing. Keeping the relative humidity in the test area between 45 % and 55 % may minimize the buildup of static. Automation software can be used to enhance the effectiveness of the static isolation unit by switching the static isolation unit on/off as required to minimize the amount of time that the TDR sampling unit is exposed to potential ESD.

4.3.6 Calibration Artifacts (Reference or Reference Standard) A precision coaxial air line with calibration traceable to a national metrology institute (such as the National Institute of Standards and Technology), 3.5 mm or 2.92 mm connectors at both ends, and at least 10 cm [3.94 in] long should be used. The characteristic impedance of the air line is based on the geometry of a coaxial transmission line using air as the dielectric between the center conductor (signal line) and the ground shield. The center conductor may be held in place by glass beads located at both ends of the air line or by the external connectors that are attached to the connectors of the air line. The uncertainty in the nominal characteristic impedance of the air line should be less than or equal ± 0.015 Z_{ref}, where Z_{ref} is the characteristic impedance of the reference air line.

4.3.7 In-Line (Transfer) Standard The transfer standard is placed between the probe and the TDR unit (see Figure 4-3). This standard could be an airline, a semi-rigid coax cable assembly with the same specifications as the flexible coax cable assemblies, or other. The transfer standard should be of

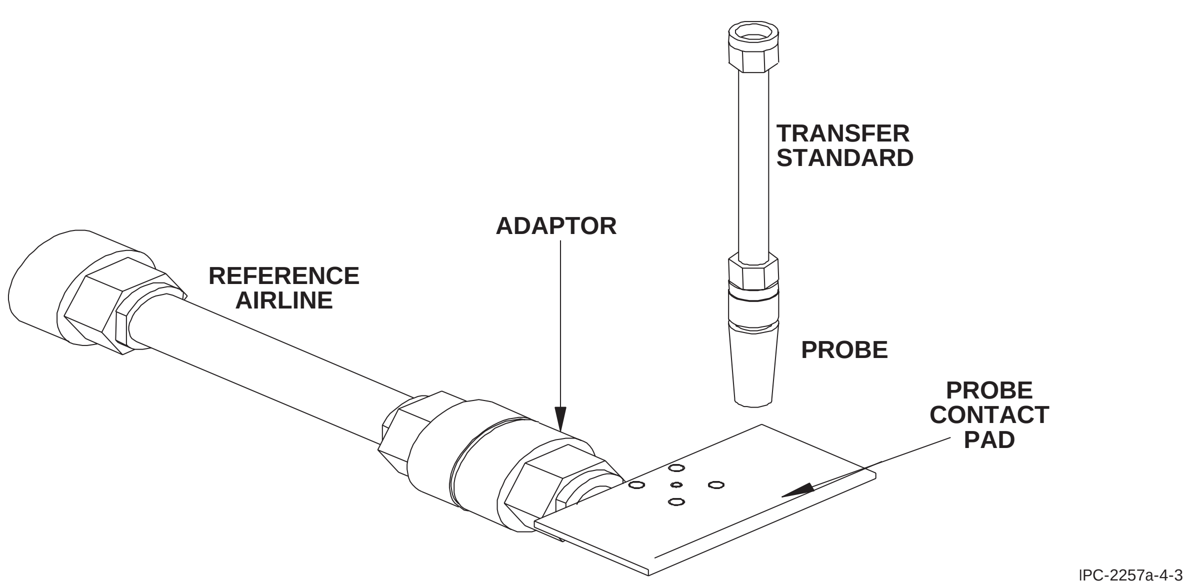

Figure 4-3 Reference Airline and Probe Contact Pad

sufficient robustness so that its impedance remains constant between calibration cycles.

4.3.8 Adapter, Airline-to-Probe Contact Pad A preferred method of calibrating the TDR amplitude response is to connect a probe contact pad directly to the airline and to probe the airline through the contact pad (see Figure 4-3). The contact pad should have a nominal characteristic impedance of 50 Ω ± 1.0 Ω. An increase in measurement accuracy can be achieved by using a reference impedance standard that is closely matched to the impedance of the transmission line to be tested.

5 Procedures

5.1 Measurement Preliminaries In this section, common considerations for the calibration of the TDR measurement system and performing the TDR measurements are provided. 5.1.3 describes a method for establishing the measurement zone that can be applied to the measurement methods described in 5.2 and 5.3.

5.1.1 System Calibration Follow the TDR instrument manufacturer's recommendation for the frequency of factory calibration. TDR system ''field'' calibrations are to be performed at regular intervals in addition to the less regular factory calibrations. The field calibrations are required for the following reasons:

a. TDR instrument specifications vary with temperature.
b. TDR instrument specifications vary with time (drift).
c. TDR instrument specifications vary due to minor ESD damage.
d. TDR instrument factory calibration usually does not include user supplied auxiliary components (e.g., cables, probes, etc.).

TDR system field calibrations should also be performed after a change of any system component (such as, cable, probes, etc.). Ensure that the TDR instrument has been operating for at least 30 minutes prior to any calibration or test measurement procedure.

Use proper ESD control methods to avoid damage to the TDR instrument in all calibration and test measurement procedures. ESD control components can include static dissipative mats, deionizer systems, and operator gowning.

5.1.2 Premeasurement Checks The test measurement should be performed after the completion of the calibration process. Ensure that plane of the signal line of a microstrip (or embedded microstrip) structure is at least a distance equal to six times the width of the microstrip signal line from any material (such as the testing table) that can affect the dielectric environment of the microstrip line. If the tests are being conducted with hand probe(s), care must be taken to ensure that the hands and/or arms of the operator do not contact any surface of the board over the transmission line being tested. Probes should be applied to the test points with sufficient force to ensure proper electrical contact between the trace and the probe assembly. Consistent application (that is, force, angle of placement, etc.) of the probes onto the test points is important to ensure repeatable measurement results.

Before recording any measurement results, ensure that the TDR waveform is stable (that is, not drifting in amplitude or time) otherwise measurement error will occur. To improve the accuracy of the impedance measurement, it is important to optimize the vertical gain setting (typically in V/div or ρ/div) and horizontal axis setting (typically in time/div) of the TDR unit so as to maximize the duration of the measurement zone within the TDR waveform and to increase amplitude resolution. Perform this TDR adjustment prior to acquiring any TDR waveforms from which Z_0 will be computed. Ensure that the temperature and humidity of the test environment is within TDR instrument specifications and is stable.

5.1.3 Establishing the Measurement Zone The value of the measurement zone is critical to the accuracy and repeatability of the TDR measurement process. Measurement zone differences are a large factor in correlation problems between measurements. The measurement zone should be set repeatability for each transmission line independent of the type of dielectric material surrounding the transmission line or its structure (surface microstrip, embedded microstrip, stripline, differential pair, etc.). The following process can be incorporated into the test measurement process. There are two measurement zones, one for the transmission line under test (see 5.1.3.1) and one for the reference (see 5.1.3.2), which may be either a transfer standard or a coaxial air line.

5.1.3.1 Procedure for the Transmission Line Under Test

Step 1 – Hold the probe in the air and locate the instant, $t_{1,TL}$, on the TDR waveform where the probe/open discontinuity occurs (see Figure 5-1). $t_{1,TL}$ is the instant in the TDR waveform when the reflection from the open circuit has reached 50 % of its amplitude (see Figure 5-1), unless otherwise specified by the user.

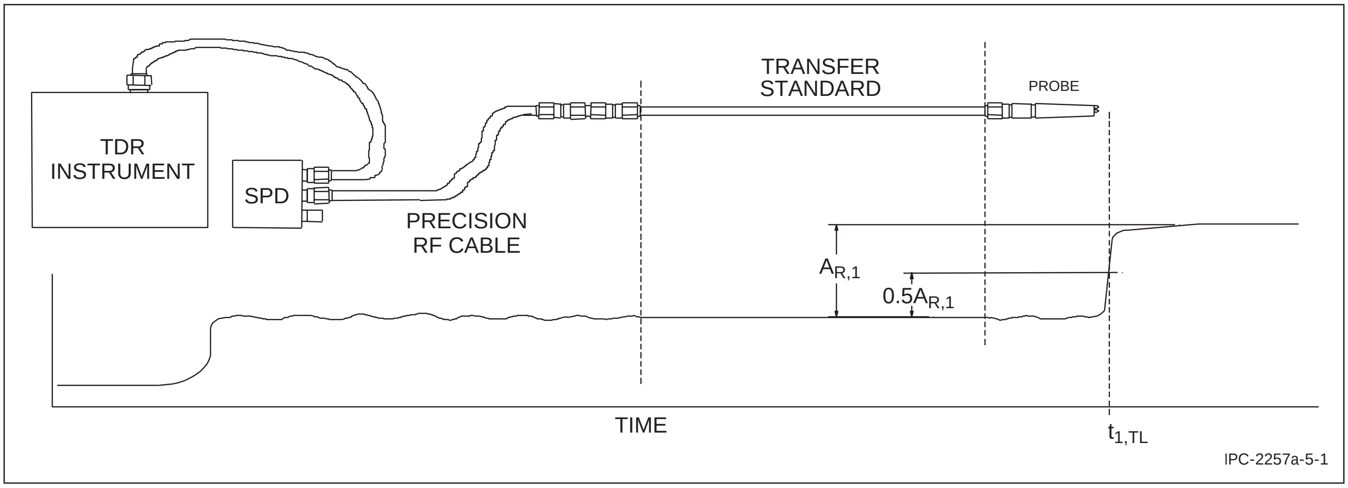

Figure 5-1 Determination of instant in the TDR waveform corresponding to the beginning of the transmission line. $A_{R,1}$ is the amplitude of the signal reflected from the open end of the probe. SPD is the static protection device (see 4.3.5).

Step 2 – Place the probe in contact with the transmission line under test and locate the instant, $t_{2,TL}$, on the TDR waveform where the transmission line/open discontinuity occurs (see Figure 5-2). $t_{2,TL}$ is the instant in the TDR waveform when the reflection from the open circuit has reached 50 % of its amplitude (see Figure 5-2), unless otherwise specified by the user.

Step 3 – Compute the round trip propagation time of the transmission line using:

$$T_{rt,TL} = t_{2,TL} - t_{1,TL}$$

Step 4 – Determine the initial instant, $t_{i,TL}$, of measurement zone (see Figure 5-3) using:

$$t_{i,TL} = t_{1,TL} + x_{i\%} T_{rt,TL}$$

where $x_{i\%}$ is the lower limit of the measurement zone and is 30 % unless otherwise specified by the user.

Step 5 – Determine final instant, $t_{f,TL}$, of measurement zone (see Figure 5-3) using:

$$t_{f,TL} = t_{1,TL} + x_{f\%} T_{rt,TL}$$

where $x_{f\%}$ is the upper limit of the measurement zone and is 70 % unless otherwise specified by the user.

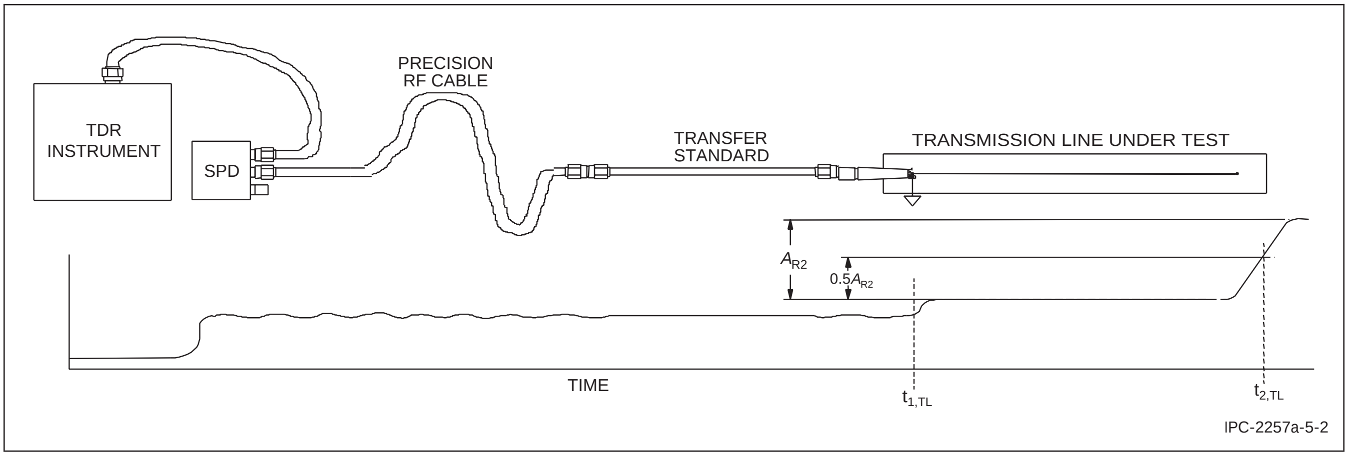

Figure 5-2 Determination of instant in TDR waveform corresponding to the end of the transmission line. $A_{R,2}$ is the amplitude of the signal reflected from the open end of the transmission line under test.

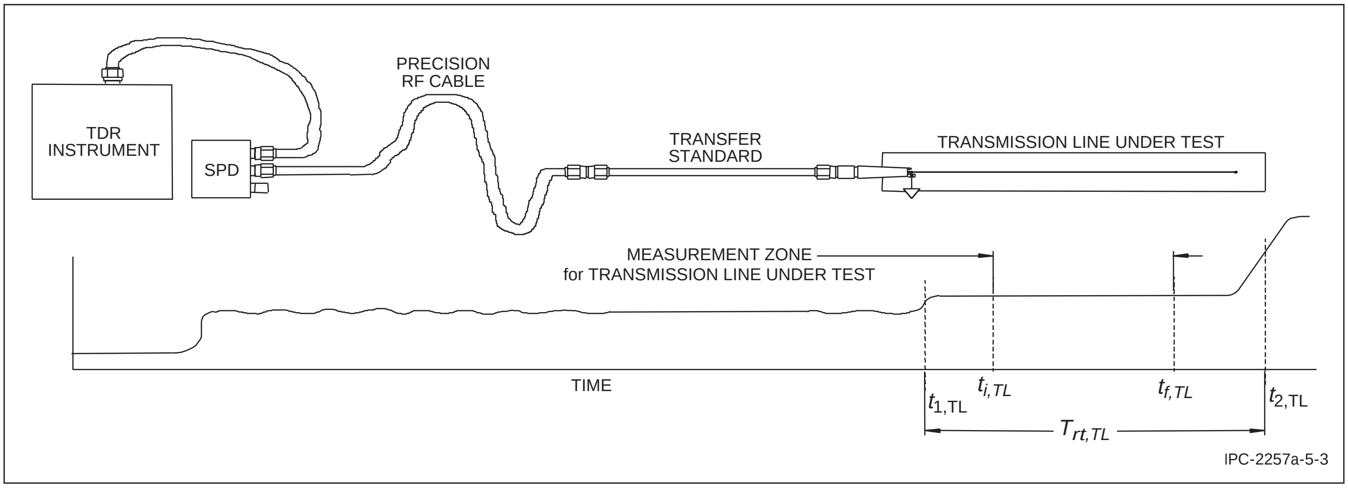

Figure 5-3 Determination of Measurement Zone

5.1.3.2 Procedure for the Reference Line

Step 1 – Remove the transfer standard (or air line reference) and hold the precision rf cable in the air and locate the instant, $t_{1,Ref}$, on the TDR waveform where the rf cable/open discontinuity occurs (see Figure 5-4). $t_{1,\mathrm{Ref}}$ is the instant in the TDR waveform when the reflection from the open circuit has reached 50 % of its amplitude (see Figure 5-4), unless otherwise specified by the user.

Step 2 – Connect the rf cable to the reference line and locate the instant, $t_{2,\mathrm{Ref}}$, on the TDR waveform where the reference line/open discontinuity occurs (see Figure 5-5). $t_{2,\mathrm{Ref}}$ is the instant in the TDR waveform when the reflection from the open circuit has reached 50 % of its amplitude (see Figure 5-5), unless otherwise specified by the user.

Step 3 – Compute the round trip propagation time of the transmission line using:

$$T_{rt,Ref} = t_{2,Ref} - t_{1,Ref}$$

Step 4 – Determine the initial instant, $t_{i,Ref}$, of measurement zone using:

$$t_{i,Ref} = t_{1,Ref} + x_{i\%} T_{rt,Ref}$$

where $x_{i\%}$ is the lower limit of the measurement zone and is 30 % unless otherwise specified by the user.

Step 5 – Determine final instant, $t_{f,TL}$, of measurement zone using:

$$t_{f,Ref} = t_{1,Ref} + \chi_{fT} T_{rt,Ref}$$

where $x_{f\%}$ is the upper limit of the measurement zone and is 70 % unless otherwise specified by the user.

5.2 Single-Ended TDR Measurement Procedures This section contains three methods for measuring the characteristic impedance of single-ended transmission lines. The following calibration and measurement steps should be used when the device(s) under test are unbalanced (single-ended) transmission lines. This process can be followed manually but, to improve measurement repeatability and reduce measurement time, an automated measurement system is recommended. Additionally, the use of a fixture based or robotic probing system greatly improves the accuracy and repeatability over hand probe techniques and further reduces the measurement time.

5.2.1 Transfer Standard Method In this method, the impedance of the reference air line is transferred to a secondary transmission line. The computed impedance of the secondary or transfer line then becomes the basis from which the characteristic impedance of all subsequent test transmission lines is computed. The transfer method provides a direct comparison of the impedance of the transfer standard to that of the transmission line under test. Although this does require two additional measurements, as compared to the in-situ method (see 5.2.2), it does reduce the risk of damage to the reference impedance standard due to frequent use and handling. The effects of drift in TDR amplitude offset are minimized with this method.

5.2.1.1 Measurement Calibration Procedure The instrument setting must be the same for Steps 1 and 2. This procedure will determine the characteristic impedance of the transfer standard from which characteristic impedance of the transmission line under test will be determined (see 5.2.1.2).

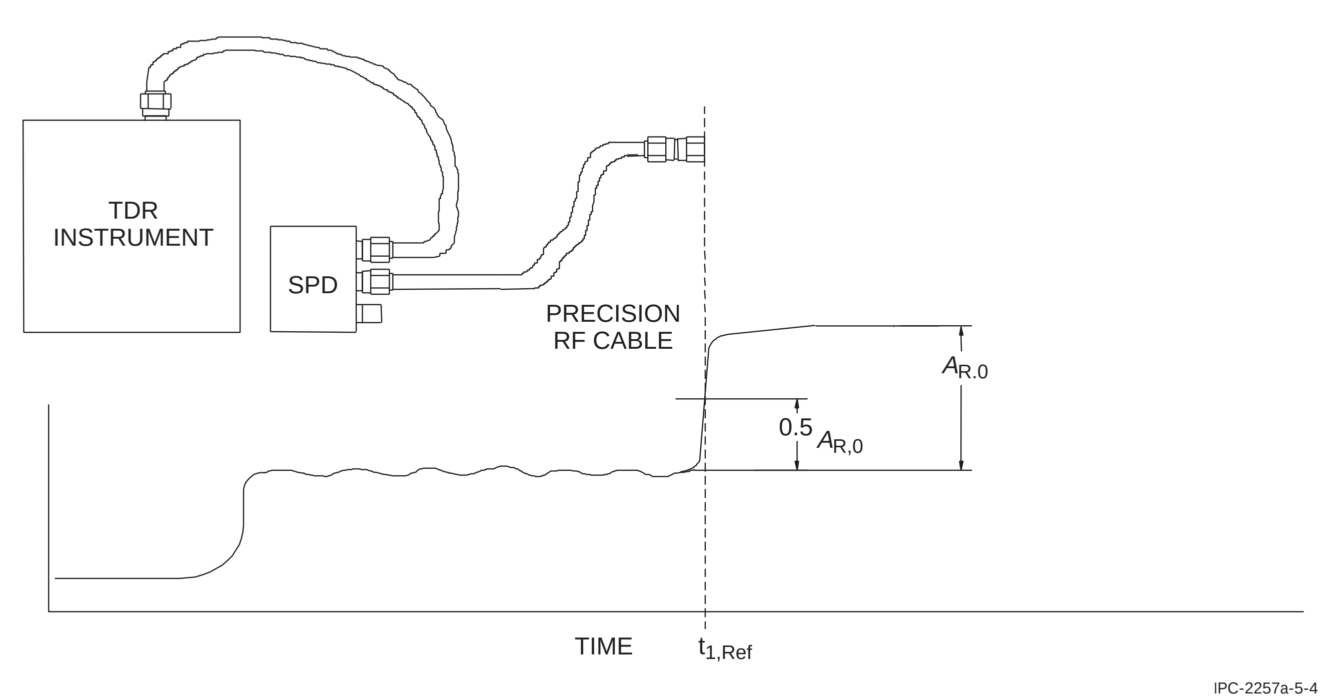

Figure 5-4 Determination of instant in the TDR waveform corresponding to the beginning of the reference line. $A_{R,0}$ is the amplitude of the signal reflected from the open end of rf cable.

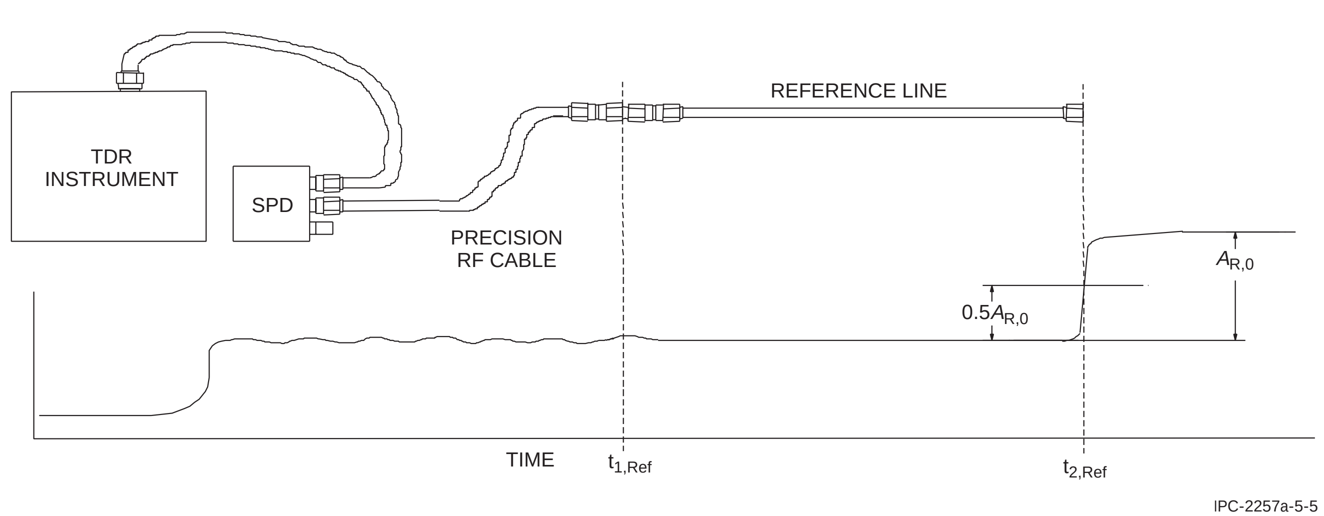

Figure 5-5 Determination of instant in TDR waveform corresponding to the end of the reference line (transfer standard or air line reference). $A_{R,0}$ is the amplitude of the signal reflected from the open end of the reference line.

Step 1 – Hold the probe in air (see Figure 5-6) and measure the average voltage levels for each of those parts of the TDR waveform corresponding to the open step, V_{open}, and to the transfer standard, $V_{tran,0}$. Calculate the amplitude, $V_{i,0}$, of the incident voltage step using:

$$V_{i,0} = V_{open} - V_{tran,0}$$

Step 2 – Probe the reference airline (see Figure 5-7) through the appropriate interface (see 4.3.8) and measure the average voltage levels for each of those parts of the TDR waveform corresponding to the airline, V_{std}, and to the transfer standard, $V_{tran,1}$, and compute the voltage difference, $V_{r,0}$:

$$V_{r,0} = V_{std} - V_{tran,1}$$

The instants, $t_{i,std}$ and $t_{f,std}$, shown in Figure 5-7 are analagous to $t_{i,TL}$ and $t_{f,TL}$ except that the former are for the air line standard from which the transfer standard impedance is determined.

Step 3 – Calculate the reflection coefficient of the transfer standard relative to the air line. If the TDR system already provides reflection coefficient values, go directly to Step 4. The reflection coefficient, ρ_{tran} for the transfer standard is given by:

$$\rho_{tran} = \frac{V_{r,0}}{V_{i,0}}$$

Step 4 – Calculate the impedance, Z_{tran}, of the transfer standard using the following formula:

$$Z_{tran} = Z_{std}\frac{1+\rho_{tran}}{1-\rho_{tran}}$$

5.2.1.2 Measurement Process The instrument setting must be the same for Steps 1 and 2. This procedure will determine the characteristic impedance of the transmission line under test. This process should be done after the measure zone has been defined (see 5.1.3).

Step 1 – Repeat the measurements of Step 1 of 5.2.1.1. Calculate the amplitude, $V_{i,1}$, of the incident voltage step using:

$$V_{i,1} = V_{open} - V_{tran,2}$$

where $V_{tran,2}$ is the average voltage level of that part of the TDR waveform corresponding to the transfer standard.

Step 2 – Probe the transmission line (see Figure 5-8) and measure the mean, minimum, and maximum voltage values, $V_{C,ave}$, $V_{C,min}$, and $V_{C,max}$, of that part of the TDR waveform corresponding to the measurement zone of the transmission line.

Step 3 – Without moving the probe from the position used in Step 2, measure the average voltage level for that part of the TDR waveform corresponding to the transfer standard, $V_{tran,3}$, and compute the voltage difference, $V_{r,1}$:

$$V_{r,1} = V_{tran,3} - V_{C,x}$$

where $V_{C,x}$ the subscript ''X'' refers to ''ave,'' ''min,'' or ''max.''

Step 4 – Calculate the reflection coefficient of the transmission line under test relative to the transfer standard. If the TDR system already provides reflection coefficient values, go

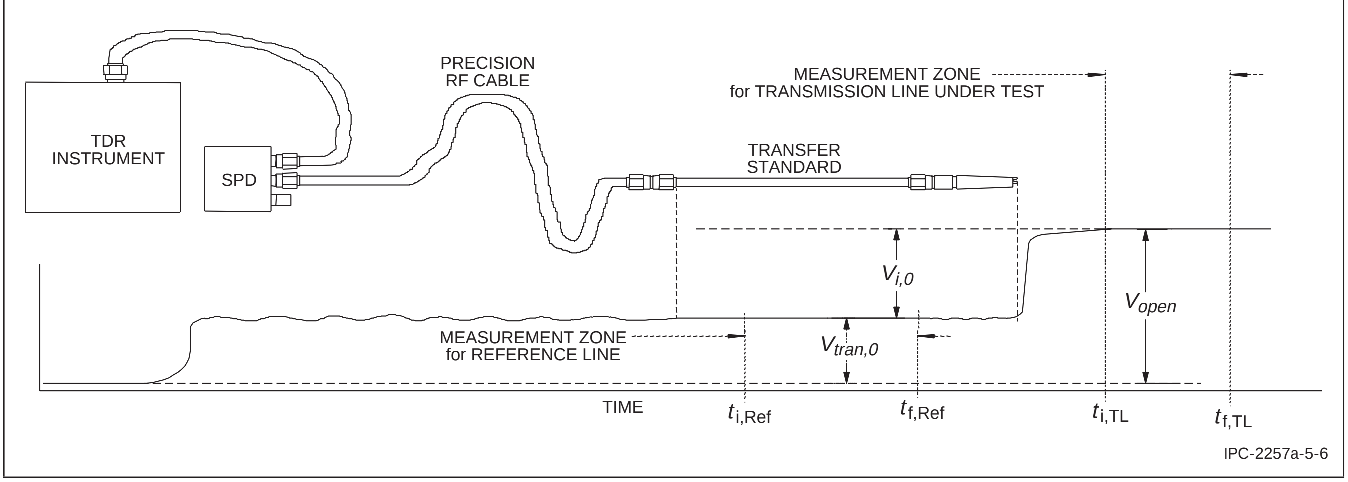

Figure 5-6 Measurement of Incident Step Amplitude

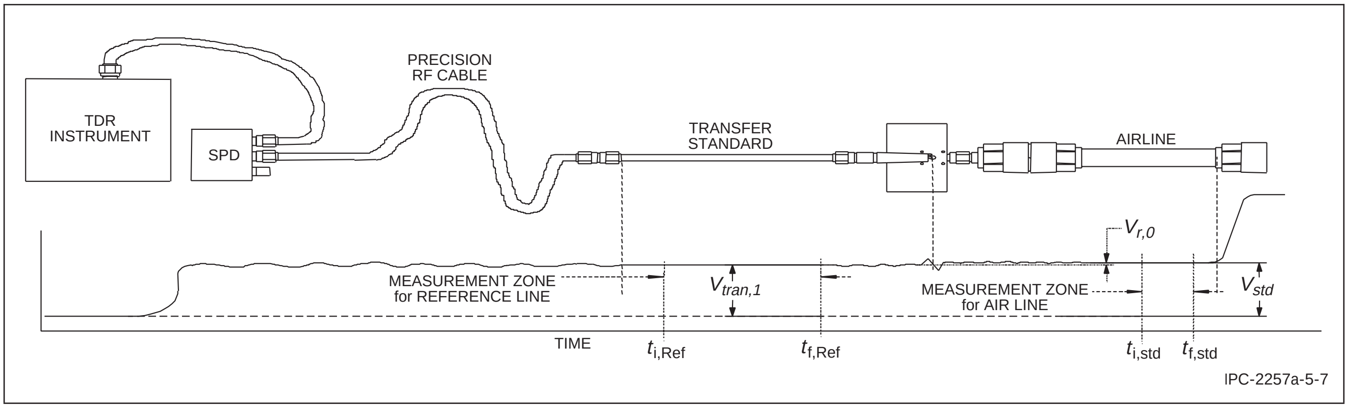

Figure 5-7 Calibration of Transfer Standard

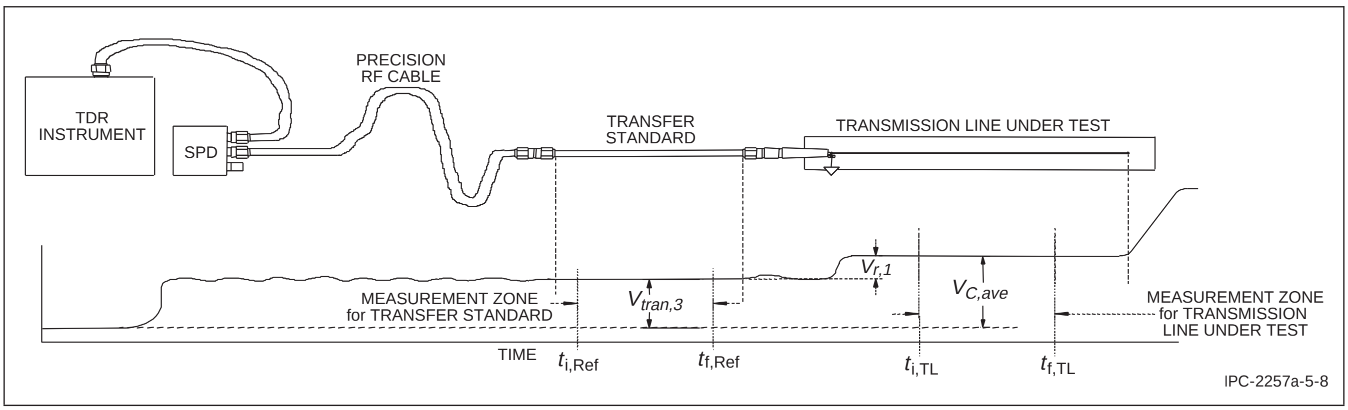

Figure 5-8 TDR Measurement of Transmission Line Under Test

directly to Step 5. The reflection coefficient, ρ_{TL} for the transmission line is given by:

$$\rho_{TL} = \frac{V_{r,1}}{V_{i,1}}$$

Step 5 – Calculate the characteristic impedance, $Z_{C,x}$, of the transmission line using:

$$Z_{C,x} = Z_{tran}\frac{1+\rho_{TL}}{1-\rho_{TL}}$$

The $Z_{C,x}$, therefore, corresponds to the average, minimum, or maximum characteristic impedance value of the transmission line under test.

5.2.2 In-situ Reference Method In this method, the impedance of the reference air line is the basis from which the characteristic impedance of all test transmission lines is computed. The in-situ reference method requires the least number of acquired waveforms compared to the other two single-ended methods described herein. This method provides a direct comparison between the reference impedance and the impedance of the transmission line under test, the other two methods do not, and this reduces the effects of drift in TDR amplitude offset on the Z_0. However, because the reference is always in use, it is more likely to become damaged and this may cause measurement error.

5.2.2.1 Measurement Calibration Procedure This method does not require a calibration step other than the general system calibration described in 5.1.1.

5.2.2.2 Measurement Process The instrument setting must be the same for Steps 1 and 2. This procedure will determine the characteristic impedance of the transmission line under test. This process should be done after the measure zone has been defined (see 5.1.3).

Step 1 – Hold the probe in air (see Figure 5-9) and measure the average voltage levels for each of those parts of the TDR waveform corresponding to the open step, V_{open}, and to the reference air line, $V_{std,0}$. Calculate the amplitude, $V_{i,0}$, of the incident voltage step using:

$$V_{i,0} = V_{open} - V_{std,0}$$

Step 2 – Probe the transmission line (see Figure 5-10) and measure the mean, minimum, and maximum voltage values, $V_{C,ave}$, $V_{C,min}$, and $V_{C,max}$, of that part of the TDR waveform corresponding to the measurement zone of the transmission line.

Step 3 – Without moving the probe from the position used in Step 2, measure the average voltage level for that part of the TDR waveform corresponding to the reference air line, $V_{std,1}$, and compute the voltage difference, $V_{r,1}$:

$$V_{r,1} = V_{std,1} - V_{C,x}$$

where $V_{C,x}$ the subscript ''X'' refers to ''ave,'' ''min,'' or ''max.''

Step 4 – Calculate the reflection coefficient of the transmission line und er test relative to the reference air line. If the TDR system already provides reflection coefficient values, go

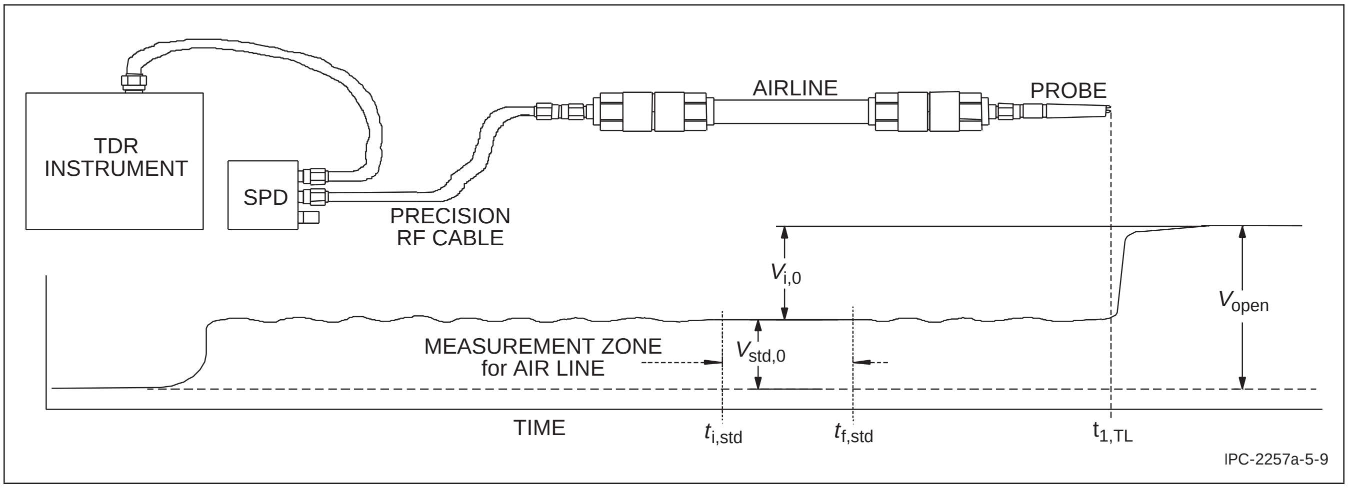

Figure 5-9 Calibration of Incident Step Amplitude

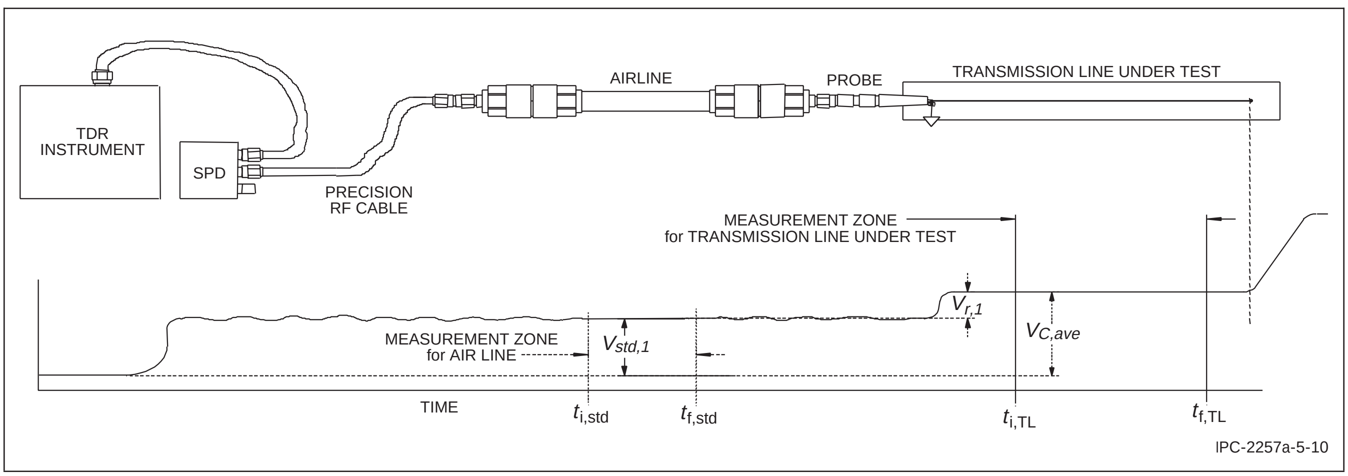

Figure 5-10 TDR Measurement of Transmission Line

directly to Step 5. The reflection coefficient, ρ_{TL} for the transmission line is given by:

$$\rho_{TL} = \frac{V_{r,0}}{V_{i,0}}$$

Step 5 – Calculate the characteristic impedance, $Z_{C,X}$, of the transmission line using:

$$Z_{C,x} = Z_{std}\,\frac{1 + \rho_{TL}}{1 - \rho_{TL}}$$

The $Z_{C,x}$, therefore, corresponds to the average, minimum, or maximum characteristic impedance value of the transmission line under test.

5.2.3 Stored Reference Waveform Method The stored reference method requires a fewer number of measurements than the transfer standard method (see 5.2.1) because the reference waveform is stored and subsequent waveforms compared to it. However, it is important in this method that the amplitude offset of the TDR unit does not drift.

5.2.3.1 Measurement Calibration Procedure The instrument setting must be the same for Steps 1 and 2. This procedure will determine the characteristic impedance of the transfer standard from which characteristic impedance of the transmission line under test will be determined (see 5.2.1.2).

Step 1 – Hold the probe in air (see Figure 5-11) and measure the average voltage levels for each of those parts of the TDR waveform corresponding to the open step, V_{open}, and to the reference standard, $V_{std,0}$. Calculate the amplitude, $V_{i,0}$, of the incident voltage step using:

$$V_{i,0} = V_{open} - V_{std,0}$$

Step 2 – Record the voltage, $V_{check,0}$, in the TDR waveform corresponding to the precision RF cable.

5.2.3.2 Measurement Process The instrument setting must be the same for Steps 1 and 2. This procedure will determine the characteristic impedance of the transmission line under test. This process should be done after the measure zone has been defined (see 5.1.3).

Step 1 – Probe the transmission line (see Figure 5-12) and measure the mean, minimum, and maximum voltage values, $V_{C,ave}$, $V_{C,min}$, and $V_{C,max}$, of that part of the TDR waveform corresponding to the measurement zone of the transmission line.

Step 2 – Record the voltage, $V_{check,1}$, in the TDR waveform corresponding to the precision RF cable and compute the following:

$$V_{diff} = \left| \frac{V_{check,0} - V_{check,1}}{V_{i,0}} \right|$$

If V_{diff} is greater than 0.002, then the TDR system must be recalibrated (see 5.2.3.1).

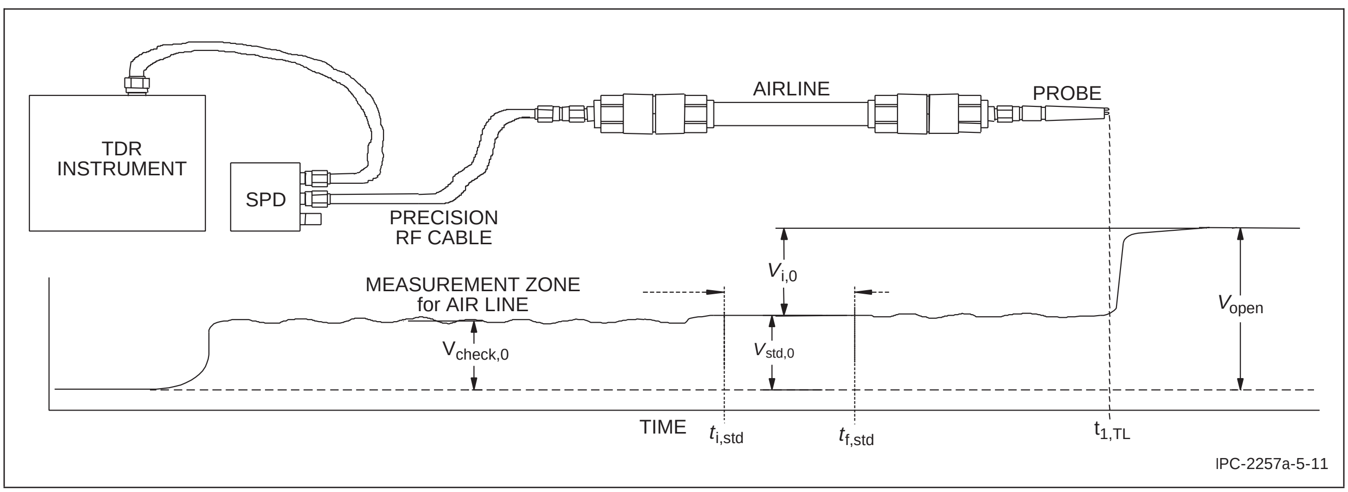

Figure 5-11 Calibration for Stored Reference Method

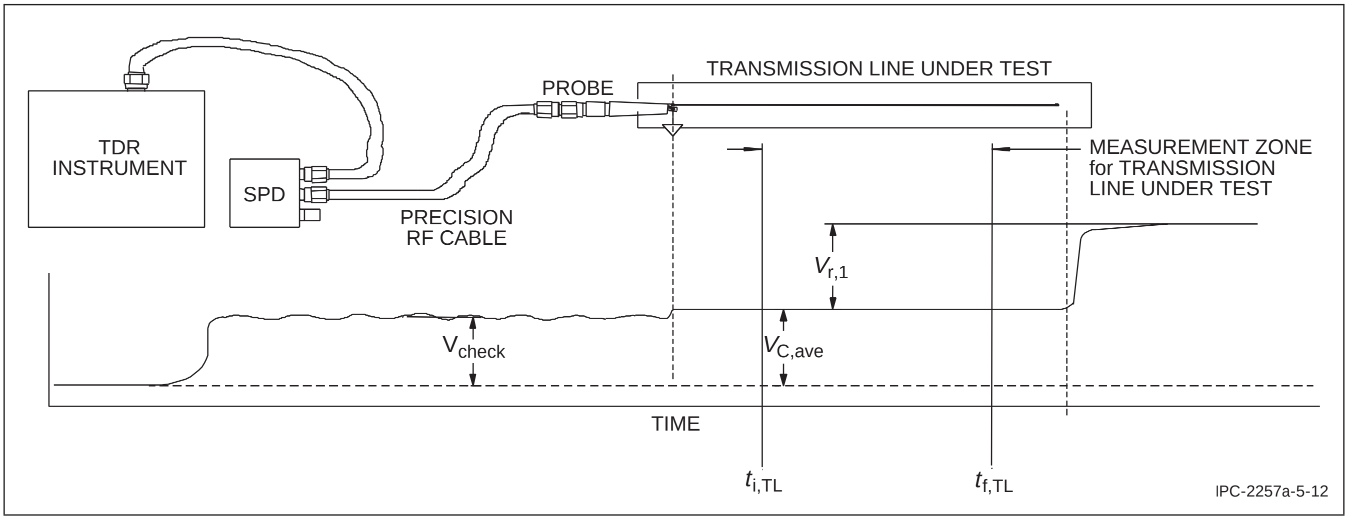

Figure 5-12 TDR Measurement of Transmission Line

Step 3 – Calculate the reflection coefficient of the transmission line under test relative to the air line. If the TDR system already provides reflection coefficient values, go directly to Step 4. The reflection coefficient, ρ_{tran} for the transfer standard is given by:

$$\rho_{tran} = \frac{V_{C,x} - V_{std,0}}{V_{i,0}}$$

Step 4 – Calculate the impedance, Z_{tran}, of the transmission line under test using the following formula:

$$Z_{tran} = Z_{std}\,\frac{1 + \rho_{tran}}{1 - \rho_{tran}}$$

5.3 Differential TDR Measurement Procedures This section contains one method for measuring the characteristic impedance of differential transmission lines. The following calibration and measurement steps should be used when the device(s) under test are differential (balanced) transmission lines. This process can be followed manually but, to improve measurement repeatability and reduce measurement time, an automated measurement system is recommended. Additionally, the use of a fixture based or robotic probing system greatly improves the accuracy and repeatability over hand probe techniques and further reduces the measurement time.

The differential method described herein requires that (1) the probe act as a transfer standard (see 4.3.3.1), (2) the TDR system uses a source that delivers a differential signal to the signal lines of the differential transmission line, and (3) the TDR samples the reflected signal from both signal lines of the differential transmission line simultaneously. In this case, two TDR waveforms are obtained, one from each of the signal lines of the differential transmission line, and these TDR waveforms are used to determine the odd mode impedance of each signal line of the differential transmission line. The odd mode impedance is not the same as the characteristic impedance of a single-ended transmission line. These odd mode impedances are then used to compute the differential impedance of the differential transmission line. For a discussion of differential impedance propagation modes refer to IPC standard 2141.

5.3.1 Instrumentation and Equipment The TDR instrument used in this test method provides two opposite-polarity equal-magnitude signals that are simultaneously applied to the two signal lines of the differential transmission line under test. A typical TDR waveform from such an instrument is shown in Figure 5-13.

Follow the manufacturer's recommended procedure and schedule for in-house as well as factory calibrations of the TDR. Prior to beginning each measurement and no less than once daily, check the skew between the two output signals of the differential source of the TDR. This skew should be checked at the output end of the probe not at the TDR output or at the end of the connecting cables. The skew should be adjusted to be a minimum. Check that the amplitude of the differential signals have equal but opposite polarity and verify that they are in specification. Use the appropriate probes (see 4.3.3.1).

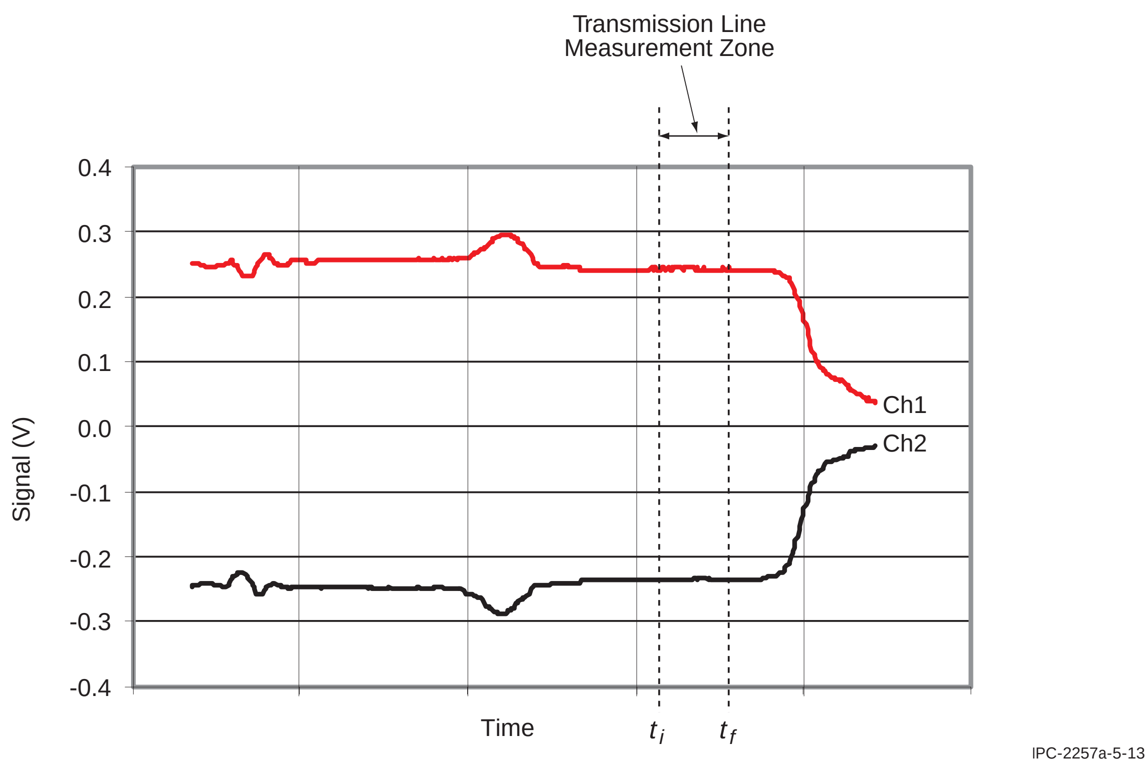

Figure 5-13 Differential TDR Waveform

5.3.2 Determination of Measurement Zone The determination of the measurement zone is done similarly to that for single-ended transmission line test methods as discussed in 5.1.3. However, for this differential test method, the TDR waveform will appear similar to that shown in Figure 5-14.

The instants shown in Figure 5-14, $t_{i,TS}$, $t_{f,TS}$, $t_{i,TL}$, and $t_{f,TL}$, are the initial and final instants of the measurements zones for the transfer standard and transmission line under test. The $t_{i,TS}$, $t_{f,TS}$ are the same as $t_{i,Ref}$ and $t_{f,Ref}$ described for single-ended transmission lines in 5.1.3.

5.3.3 Measurement Calibration Procedure The instrument setting must be the same for Steps 1 and 2. This procedure will determine the characteristic impedance of the transfer standard from which characteristic impedance of the transmission line under test will be determined (see 5.3.4).

Step 1 – Hold the probe in air and measure the average voltage levels corresponding to the high and low states of the two differential TDR waveforms, which are labeled $V_{TS,Ch1,1}$, $V_{TS,Ch2,1}$, $V_{open,Ch1}$, and $V_{open,Ch2}$ in Figure 5-15. There are a total of four states, two for each of the differential waveforms. Calculate the amplitude, $V_{inc,Ch1}$, of the incident voltage step for Channel 1 (Ch1) using:

$$V_{inc,Ch1} = V_{TS,Ch1,1} - V_{open,Ch1}$$

and the amplitude, $V_{inc,Ch2}$, of the incident voltage step for Channel 2 (Ch2) using:

$$V_{inc,Ch2} = V_{TS,Ch2,1} - V_{open,Ch2}$$

where:

$V_{TS,Ch1,1}$ is the average voltage level of that part of the Ch1 TDR waveform corresponding to the transfer standard,

$V_{TS,Ch2,1}$ is the average voltage level of that part of the Ch2 TDR waveform corresponding to the transfer standard,

$V_{open,Ch1}$ is the average voltage level of that part of the Ch1 TDR waveform corresponding to the high state of the differential signal applied to Ch1, and

$V_{open,Ch2}$ is the average voltage level of that part of the Ch2 TDR waveform corresponding to the high state of the differential signal applied to Ch2.

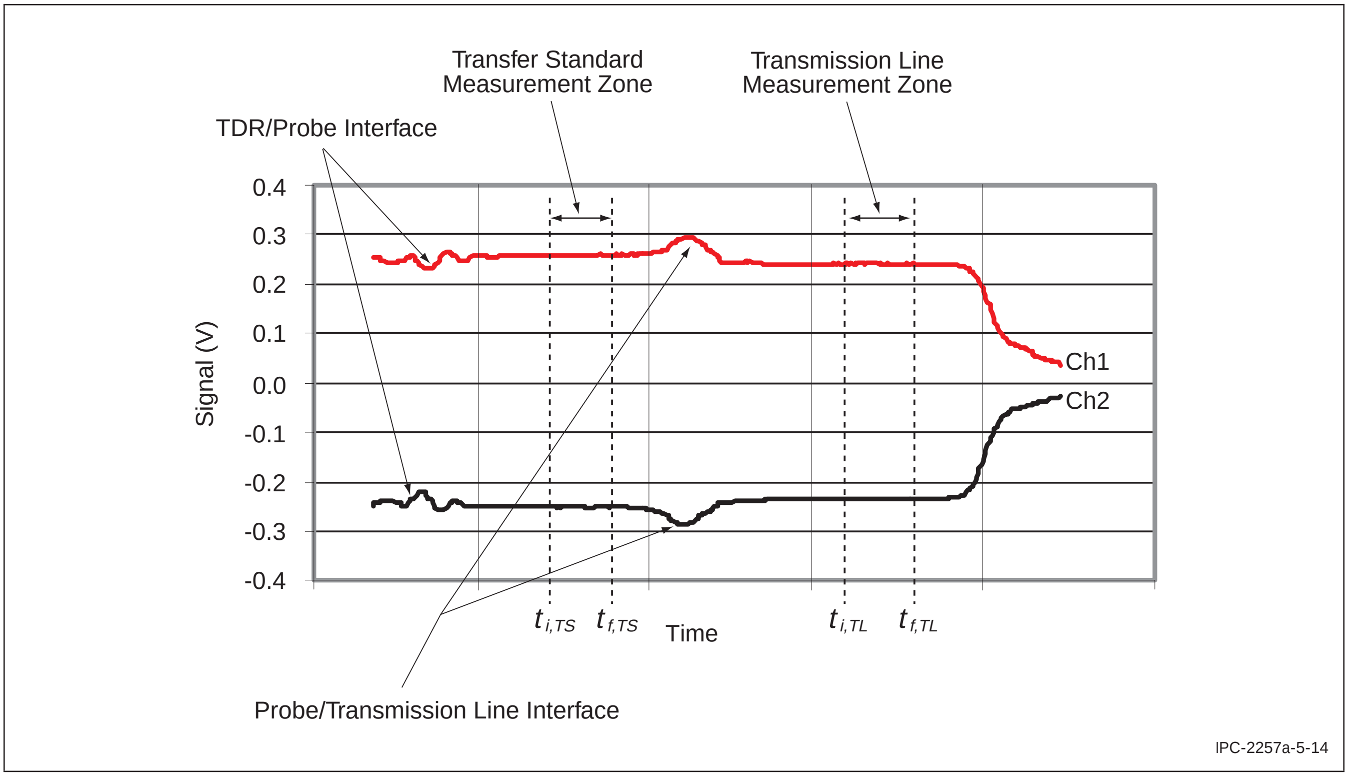

Figure 5-14 Measurement Zones for Differential TDR

Step 2 – Probe the reference airline using suitable adapter and obtain a TDR waveform similar to that shown in Figure 5-16 for each channel. Measure the average voltage levels for the high and low states for the two differential TDR waveforms, which are labeled $V_{TS,Ch1,2}$, $V_{TS,Ch2,2}$, $V_{std,Ch1}$, and $V_{std,Ch2}$ in Figure 5-16. There are a total of four states, two for each of the differential waveforms. Calculate the voltage difference, $V_{r,Ch1}$, for Channel 1 (Ch1) using:

$$V_{r,Ch1} = V_{TS,Ch1,2} - V_{std,Ch1}$$

and the voltage difference, $V_{r,Ch2}$, for Channel 2 (Ch2) using:

$$V_{r,Ch2} = V_{Ts,Ch2,2} - V_{std,Ch2}$$

where:

$V_{TS,Ch1,2}$ is the average voltage level of that part of the Ch1 TDR waveform corresponding to the transfer standard (not the same value as used in Step 1),

$V_{TS,Ch2,2}$ is the average voltage level of that part of the Ch2 TDR waveform corresponding to the transfer standard (not the same value as used in Step 1),

$V_{std,Ch1}$ is the average voltage level of that part of the Ch1 TDR waveform corresponding to the reference standard (the airline), and

$V_{lo,Ch2}$ is the average voltage level of that part of the Ch2 TDR waveform corresponding to the reference standard (the airline).

This calibration step can be performed using either one reference airline or two. Because the reference airline contains only one signal conductor, if one airline is used, then calibration of the two channels must be performed sequentially (in which case, Figure 5-16 is a composite of two TDR waveforms, one for each differential TDR channel). If two airlines are used, then the calibration of the two channels can be performed simultaneously.

Step 3 – Calculate the characteristic impedance, $Z_{TS,Ch1}$, of the transfer standard for Channel 1 (Ch1) using:

$$Z_{TS,Ch1} = \left(\frac{V_{inc,Ch1} - V_{r,Ch1}}{V_{inc,Ch1} + V_{r,Ch1}}\right) Z_{std}$$

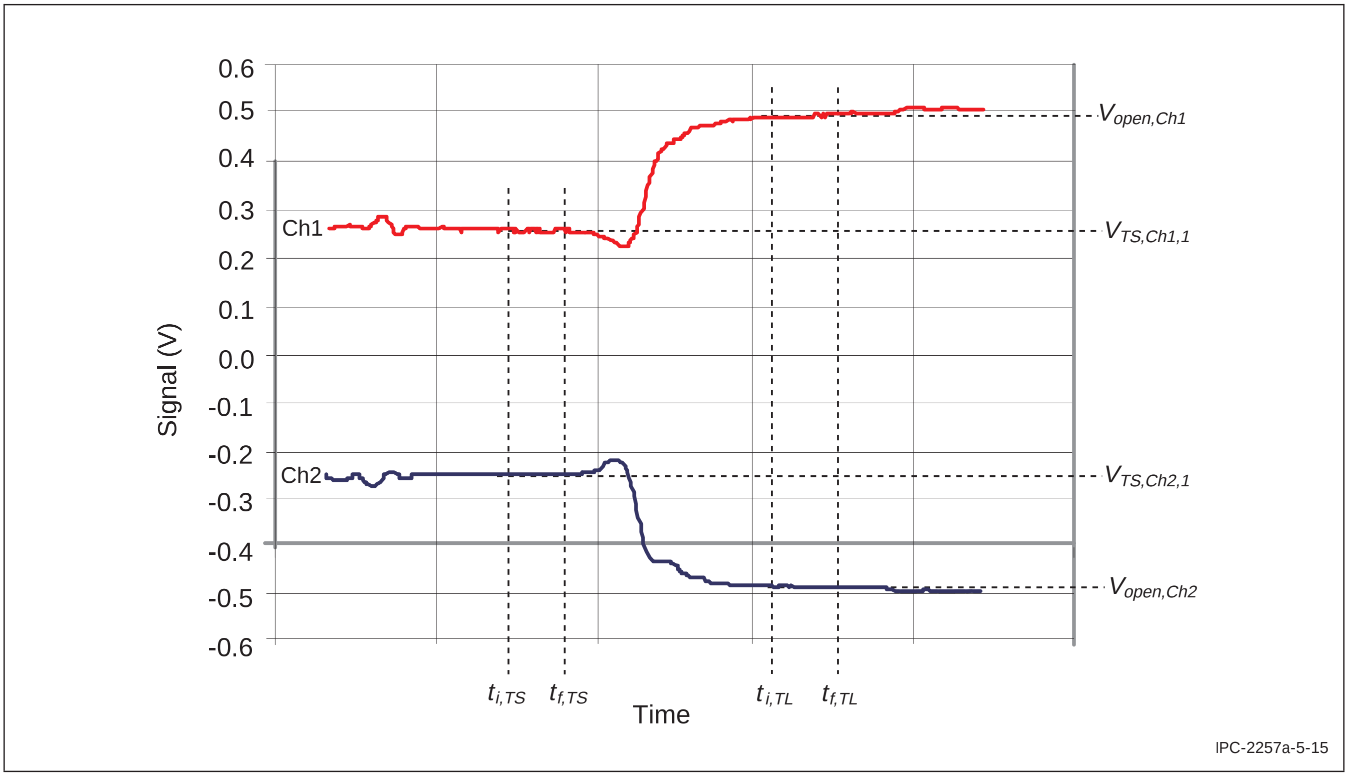

Figure 5-15 Measuring Amplitude for Incident Step

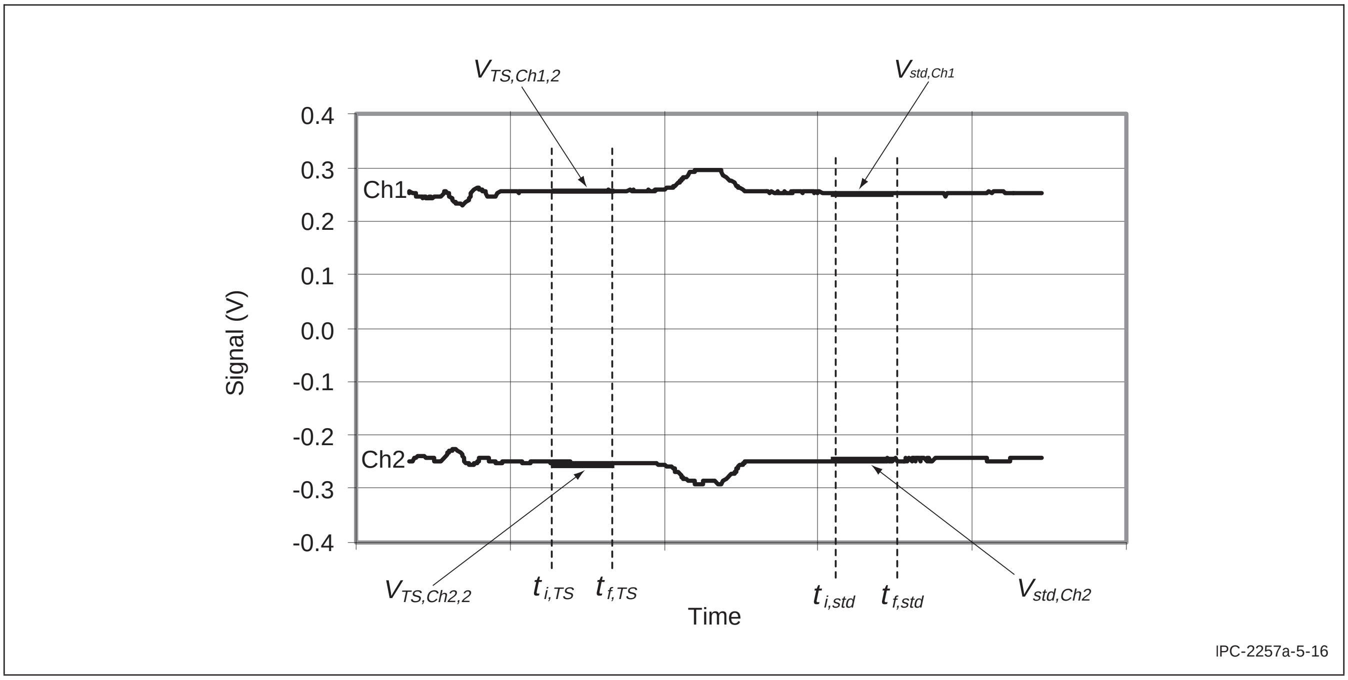

Figure 5-16 Calibration of Transfer Standard

and the characteristic impedance, $Z_{TS,Ch2}$, of the transfer standard for Channel 2 (Ch2) using

$$Z_{TS,Ch2} = \left(\frac{V_{inc,Ch2} - V_{r,Ch2}}{V_{inc,Ch2} + V_{r,Ch2}}\right) Z_{std}$$

where:

Z_{std} the characteristic impedance of the reference standard (the airline).

5.3.4 Transmission Line Measurement Process The instrument setting must be the same as that for 5.3.3. This process should be done after the measure zone has been defined (see 5.3.2).

Step 1 – Probe the transmission line and measure the average voltage levels for the high and low states for the two differential TDR waveforms, which are labeled $V_{TS,Ch1,3}$, $V_{TS,Ch2,3}$, $V_{TL,Ch1}$, and $V_{TL,Ch2}$ in Figure 5-17. There are a total of four states, two for each of the differential waveforms. Calculate the voltage difference, $V_{r,Ch1,TL}$ for Channel 1 (Ch1) using:

$$V_{r,TL,Ch1} = V_{TS,Ch1,3} - V_{TL,Ch1}$$

and the voltage difference, $V_{r,Ch2,TL}$ for Channel 2 (Ch2) using:

$$V_{r,TL,Ch2} = V_{TS,Ch2,3} - V_{TL,Ch2}$$

where:

$V_{TS,Ch1,3}$ is the average voltage level of that part of the Ch1 TDR waveform corresponding to the transfer standard (not the same value as used in 5.3.3, Steps 1 and 2),

$V_{TS,Ch2,3}$ is the average voltage level of that part of the Ch2 TDR waveform corresponding to the transfer standard (not the same value as used in 5.3.3, Steps 1 and 2),

$V_{TL,Ch1}$ is the average voltage level of that part of the Ch1 TDR waveform corresponding to the transmission line under test, and

$V_{TL,Ch2}$ is the average voltage level of that part of the Ch2 TDR waveform corresponding to the transmission line under test.

Step 2 – Calculate the odd-mode impedance, $Z_{odd,Ch1}$, for the signal line of the transmission line under test connected to Channel 1 (Ch1) using:

$$Z_{odd,Ch1} = \left(\frac{V_{inc,Ch1} - V_{r,TL,Ch1}}{V_{inc,Ch1} + V_{r,TL,Ch1}}\right) Z_{TS,Ch1}$$

and the odd-mode impedance, $Z_{odd,Ch2}$, for the signal line of the transmission line under test connected to Channel 2 (Ch2) using:

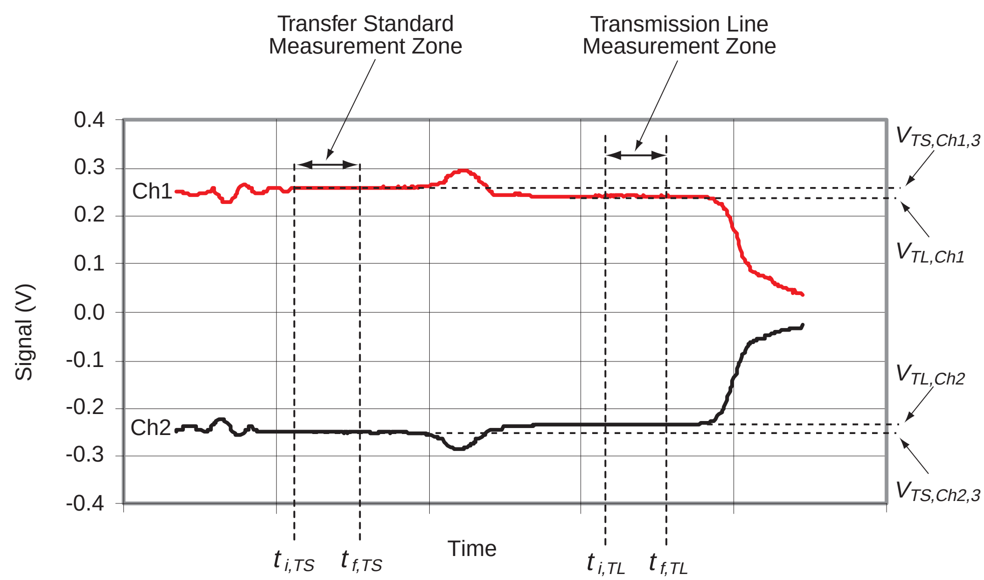

Figure 5-17 Differential TDR Measurement of Transmission Line

$$Z_{odd,Ch2} = \left(\frac{V_{inc,Ch2} - V_{r,TL,Ch2}}{V_{inc,Ch2} + V_{r,TL,Ch2}}\right) Z_{TS,Ch2}$$

where:

$Z_{TS,Ch1}$ is the characteristic impedance of the transfer standard connected to Ch1 as determined in Step 3 of 5.3.3,

$Z_{TS,Ch2}$ is the characteristic impedance of the transfer standard connected to Ch2 as determined in Step 3 of 5.3.3,

$V_{r,TL,Ch1}$ is the reflected voltage value from Ch1 as calculated in Step 1,

$V_{r,TL,Ch2}$ is the reflected voltage value from Ch2 as calculated in Step 1,

$V_{inc,Ch1}$ is the voltage amplitude computed for Ch1 in Step 1 of 5.3.3, and

$V_{inc,Ch2}$ is the voltage amplitude computed for Ch2 in Step 1 of 5.3.3.

Step 3 – Calculate the differential impedance, $Z_{TL,diff}$, of the transmission line under test using:

$$Z_{TL,diff} = Z_{odd,Ch1} + Z_{odd,Ch2}$$

6 Special Considerations and Notes

6.1 General

6.1.1 Quality Control Measurements for manufacturing control are performed to identify and correct process or materials problems occurring during a manufacturing run, as well as to assure that a product will perform electrically as designed. To facilitate the large number of measurements required in a production environment and to maximize measurement repeatability and reproducibility between different operators and test systems, it is particularly useful to automate the TDR calibration and measurement by using computer control. This can be easily achieved using a personal computer and suitable equipment as described in Section 4. Examples of parameter variations detectable by TDR, and that are evidence of process or materials problems, include the following:

a. Over/under-retching (line width problems).

b. Over/under-plating (line width and thickness problems).

c. Permittivity of the dielectric.

d. Thickness of the dielectric.

e. Degradation from excessive heating and humidity.

f. Damage from excessive pressure during the multilayer process.

g. Variations in the laminate glass-to-resin content.

h. Variations in additional coatings applied to the board surface, e.g., solder mask.

Measurement repeatability is described in IPC-TM-650 Test Method 1.9, *Measurement Precision Estimation for Variables Data.* This test method also describes a process to evaluate the reproducibility of a measurement system for multiple operators, on different days, and when using different instruments. This evaluation process should be followed and a precision-to-tolerance ratio acceptable to the customer obtained.

6.1.2 Single-Ended and Differential Lines Increased performance requirements for computer and other electronic products often demand even greater signal fidelity, time precision, and noise immunity, than can be obtained with a single-ended transmission line. A single-ended transmission line is a transmission line design consisting of a single signal conductor placed over one ground plane, as in microstrip, or between two ground planes, as in stripline. Single-ended lines may be called unbalanced transmission lines. Differential lines are used to increase signal fidelity with improved time precision and increased noise immunity. Differential lines may also be called balanced or coupled transmission lines. The required TDR method is different for differential lines.

6.1.3 Environmental Factors Temperature and humidity should be monitored during the test. Long exposures to temperatures and humidities other than standard laboratory conditions (temperature range of 20 °C to 23 °C [68 °F to 73.4 °F] and relative humidity range of 35 % to 65 %) can impact the dielectric properties of the materials in the test objects. Furthermore, the electrical characteristics of the TDR, such as sampler gain, are temperature dependent. Therefore, for the most repeatable measurements, the TDR instrumentation should be maintained within the manufacturer recommended temperature and humidity ranges. Low relative humidity may result in electrostatic discharge damage to the TDR unit.

6.1.4 Measurement Accuracy and Repeatability Accuracy and repeatability depend on the impedance of the line being measured, the type and condition of probes, cables, sampling head, and the experience of the test technician. Accuracy is the difference between the most likely measurement and the defined standard. The most likely measurement is also called the mode of all measurements within a sample set. Three times the standard deviation around each side of the mode is the repeatability.

The ability to resolve a measurement value is fundamental to the accuracy of any measurement process. The TDR instrument should have sufficient measurement resolution to facilitate the accuracy requirements of the measurement method described herein. The total risetime of the TDR system (including cables, probes, etc.) and step aberrations define the impedance resolution (see 4.1.2).

6.1.5 General Cautionary Statement TDR test systems and associated accessories are precision high frequency devices. Most TDRs include hardware to protect the static-sensitive sampling heads. However, operators and maintenance staff should take proper ESD precautions (see manufacturer's recommendations). High frequency cables, because they typically use solid center conductors, are not as flexible as typical coaxial cable. Consequently, care should be taken not to excessively bend and flex the high frequency cables. The probes used in TDR systems typically use spring-loaded contacting mechanisms and these should be checked periodically to ensure proper operation. Statistical process control methods and control charts can provide useful information regarding the condition of the TDR system and its associated accessories.

6.1.6 TDR Measured Values The units of the values output by the TDR system may be in voltage, reflection coefficient (commonly called ''rho'' for the Greek character, ρ, representing it), and impedance.

6.1.6.1 Impedance If the TDR system provides impedance values directly, no further computation is required to obtain the characteristic impedance of the transmission line under test.

6.1.6.2 Reflection coefficient, ρ If the TDR unit provides its output in terms of ρ, then the characteristic impedance of the transmission line under test must be computed from ρ.

6.1.6.3 Voltage If the TDR unit provides its output in term of voltages, these voltages must first be used to compute the amplitude of the incident and reflected pulses. Note, all voltages values measured in the test procedures are that of static voltage levels. These voltage levels are used to compute pulse amplitudes. The pulse amplitudes, in terms of voltage, are then used to compute the reflection coefficient of the transmission line under test relative to the TDR, as shown in the test methods, and these reflection coefficients are then used to determine the characteristic impedance of the transmission line under test.

6.2 Calibration

6.2.1 System Verification The use of test reference specimens corresponding to different impedance values, for example 28 Ω, 50 Ω, and 100 Ω for single-ended transmission lines and 100 Ω for differential transmission lines, should be measured according to the user-defined sampling plan and compared to impedance control limits to ensure the system is functioning correctly.

6.2.2 Calibration Artifacts Air line standards should be checked for mechanical tolerances or replaced at regular intervals. They should be handled with care. Worn out standards can cause a significant but unknown error than can exceed 2 Ω. The air line should be compared to another air line periodically to verify the air line in use has not been damaged. The airline should also be calibrated and documented periodically (not less than once every two years) by a qualified certification laboratory and kept in an environment safe from mechanical shocks, dust and dirt. Dust and dirt degrade the fine threads of the connection and damage the electrical mating surfaces. Also, some TDR equipment manufacturers have requirements for the minimum length of the airlines they recommend for calibration and standardization. Check with the manufacturer regarding their calibration requirements. For differential impedance of 100 Ω, each channel can be checked with a 50 Ω airline.

Ideally, the effects of material properties of the air line should be included in the calculation of the air line impedance because some of the corresponding transmission line properties, such as conductor resistance, will be frequency dependent. Also, beadless air lines should be used because their geometries can be readily measured whereas the geometries of beaded air lines are more difficult to measure.

6.3 Measurement System

6.3.1 Bandwidth/Risetime Resolution The frequency components of the TDR step are approximately related to the bandwidth by:

$$BW_{-3dB} \approx \frac{0.35}{t_d}$$

where:

BW_{-3dB} is the 3 dB attenuation bandwidth and t_d is the 10 % to 90 % transition duration of the TDR step response.

Note that this relationship may not accurately represent the intended operational frequencies of the transmission line being tested. The bandwidth and risetime characteristics must be adequate to ensure that the TDR can provide a measurement zone long enough to accurately determine Z_0 for a transmission line of a given length. This constant-valued region corresponds to the round-trip propagation time of the TDR step on the transmission line being tested. If the TDR transition duration is too long relative to this propagation time, the constant-valued region (also called the measurement zone) will be very short thereby increasing measurement error and uncertainty. Risetime considerations, however, are not the best method for determining TDR resolution. It is better to consider the temporal/spatial resolution of the TDR (see 4.1.2) than bandwidth/risetime resolution when determining the performance of the TDR measurement system.

6.3.2 Temporal/Spatial Resolution The TDR unit may not be the only limiting factor for temporal resolution. The probe connecting the TDR unit to the test specimen may also limit resolution and this needs to be considered. Because of the nature of TDR, it is easy to include the effects of the TDR unit and all of the probe devices collectively, by defining t_{sys} as the fall time of the TDR step that has reflected from a short circuit placed at the end of the probe and returned to the TDR head. The mean value of Z_0 is less susceptible to TDR resolution than are the minimum and maximum values.

6.3.3 Amplitude Scale If a coarse vertical scale is used, quantization error can be significant. Many instruments change accuracy when their scales are changed, and this can result in significant but unknown errors that can exceed 3 Ω.

6.3.4 Baseline and Amplitude Drift The ability of the TDR instrument to maintain a constant baseline voltage and constant amplitude step pulse are critical to the repeatability of the TDR measurement process. TDR step generators and sampling units are sensitive to time and temperature drifts. Drift should be minimized and have a value that corresponds to less than one-tenth the desired impedance uncertainty.

6.3.5 Electrostatic Discharge Damage ESD damage to TDR instrumentation is often not easily detected and may unknowingly affect measurement accuracy. Therefore, system calibration should be performed regularly to check for this (see 5.1.1). All cables should have a termination attached to one end when not in use and while they are being connected to the TDR instrumentation. The use of a static protection switch helps eliminate ESD damage to the TDR. Operators should have anti-static awareness training and should perform all measurements in anti-static work areas while wearing anti-static wrist straps.

6.3.6 Probes Hand-held (manual) probing solutions are more sensitive to operator technique than are automated methods and, consequently, the measurements made using manual probing methods will exhibit higher variability than automated methods. Operators should be trained and tested in their ability to repeatably probe and obtain a consistent measurement.

6.3.6.1 Probes for Single-Ended Transmission Line Measurements The probe assembly impedance is often chosen to be 50 Ω to match the impedance of the TDR system. Impedance matching minimizes reflections at the interface between the probe and the transmission line under test. These reflections, which appear at and around the transition region in the TDR pulse and can extend for some time after this transition, are perturbations in the TDR waveform and are undesirable because they affect the length of the measurement zone and may increase measurement uncertainty. When the characteristic impedance of the transmission line under test is nominally 50 Ω, these perturbations will normally decay rapidly. If the impedance of the transmission line under test is significantly different from 50 Ω, the magnitude of the perturbations can be large and their duration long enough to affect the measurement zone. The effect of these perturbations must be taken into account when determining the measurement zone (see 4.1.2). The design and quality of manufacture of the probe has a large effect on the magnitude and duration of reflections generated between the TDR system and the transmission line under test.

When probing non-50 Ω lines, it is possible to separate, in the TDR waveform, the large signal perturbations caused by the TDR/probe interface from those caused by the probe/transmission line interface. To do this, a specially designed probe is required that is impedance matched to the transmission line under test and that also has a long propagation delay between the TDR/probe connection and the probe tip. The long propagation delay can effectively move the large perturbations at the TDR/probe interface out of the measurement zone.

6.3.6.2 Probes for Coupled-Signal-Line (Differential) Transmission Line Measurements The probe considerations described in 4.3.3 apply for probes used in differential transmission line measurements. However, the necessity to simultaneously probe two signal lines and one or two reference plane contacts makes differential probing more difficult than probing single signal line structures. In a PCB manufacturing environment, the use of two probes that were previously used for single-ended measurements may not be possible. This is because the operator is required to use both hands for probing, which leaves them unable to operate the instrument. Contact your instrument manufacturer for their probing solutions and advice. Probes from one manufacturer can also be used with another manufacturer's TDR if the impedance values and connectors are compatible.

6.4 Adjustable Measurement Parameters

6.4.1 Sampling Interval (Point Spacing) The temporal resolution of the TDR unit is an issue only if it impacts the duration of the constant-valued regions in the TDR waveform (see 4.1.2) that are used for computing Z_0. The temporal resolution of the TDR is affected by the transition duration of the TDR step response, the transition duration of the step response of all intervening electrical components (connectors, cables, adapters), measurement jitter, the interval between sampling instances, and timebase errors. For typical TDR measurements, timebase errors and sampling intervals should not be an issue (both are or can be made to be less than 10 ps). The effect of measurement jitter can be modeled by convolving the jitter distribution with the TDR step response to yield an effective TDR step response. The effect of jitter on the bandwidth of the TDR measurement can be assessed from the jitter spectrum, which can be described by:

$$J(f) = e^{-2(\pi\sigma f)^2}$$

where:

J is the jitter spectrum,
f is frequency, and
σ is the rms jitter value

If the effective step response impacts the duration of the measurement zones, then jitter must be reduced. If the jitter has an observable effect, then the user must reduce the duration of the measurement zone (by increasing the lower limit and decreasing the upper limit, (see 5.1.3) from which Z_0 is computed or reduce the system jitter. Reduction in the duration of the measurement zone may introduce a bias in the voltage or reflection coefficient values and this affect the computed value of Z_0. If the rms jitter value is less than 20 % of the transition duration of the TDR step response, then the jitter is small and can be ignored. For typical TDR systems, however, rms jitter is less than 10 ps and will not affect the Z_0 measurements. Similarly, the effect of cables, connectors, and adapters on the measurement can be modeled by convolving their step responses with that of the TDR unit. If the transition duration of this new step response meets the requirements of 4.1.2, then the performance of the cables, connectors, and adapters is adequate.

6.4.2 Waveform Averaging and Number of Samples in the Measurement Zone Waveform averaging reduces the effective noise level of the measurement by $M^{-1/2}$, where M is the number of acquired waveforms (typically, $8 \leq M \leq 256$). Consequently, averaging can reduce measurement noise. This reduction is limited by the number of bits of the analog-to-digital converter of the TDR system. However, if the TDR-system exhibits drift in the timebase, averaging too many waveforms may result in a reduction of t_{sys} and a commensurate reduction in the temporal/spatial resolution of the TDR.

The number of samples (data points) in the measurement zone will affect the standard deviation of the computed value of Z_0 because this value is the result of averaging all the samples in the measurement zone. Therefore, the more samples in the measurement zone, the smaller will be the standard deviation of the computed Z_0 value.

6.4.3 Selection of Constant-Valued Region (Measurement Zone) Inconsistency in defining where the constant-valued region is located in the TDR waveform may cause a significant but unknown error than can exceed 5.0 Ω. Specifying the measurement zone improves measurement repeatability of the same or similar samples, and this can improve assessment of design and fabrication quality and vendor capability. This measurement zone should be far enough away from the launch and the open end of the transmission line under test to minimize the effects of these discontinuities. The measurement zone is to be given as the separation between two positions on the transmission line, and these positions are to be given as a percentage of the transmission line length referenced from the TDR/transmission line interface. The measurement zone is defined in 5.1.3.

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